C^+ and The Connection Between Different Tracers of The Diffuse Interstellar Medium

Steve Federman, University of Toledo;
Johnathan Rice, University of Toledo;
Jorge Pineda, JPL, California Institute of Technology;
William Langer, JPL, California Institute of Technology;
Paul Goldsmith, JPL, California Institute of Technology;
Nicolas Flagey, Institute for Astronomy, Hilo, HI

Outline

- Introduction
  - GOTC+
  - Cloud Types
- GOTC+
  - CO Dark gas
  - Indicators
- Observations
- Results
- Summary

GOTC$^+$ Overview

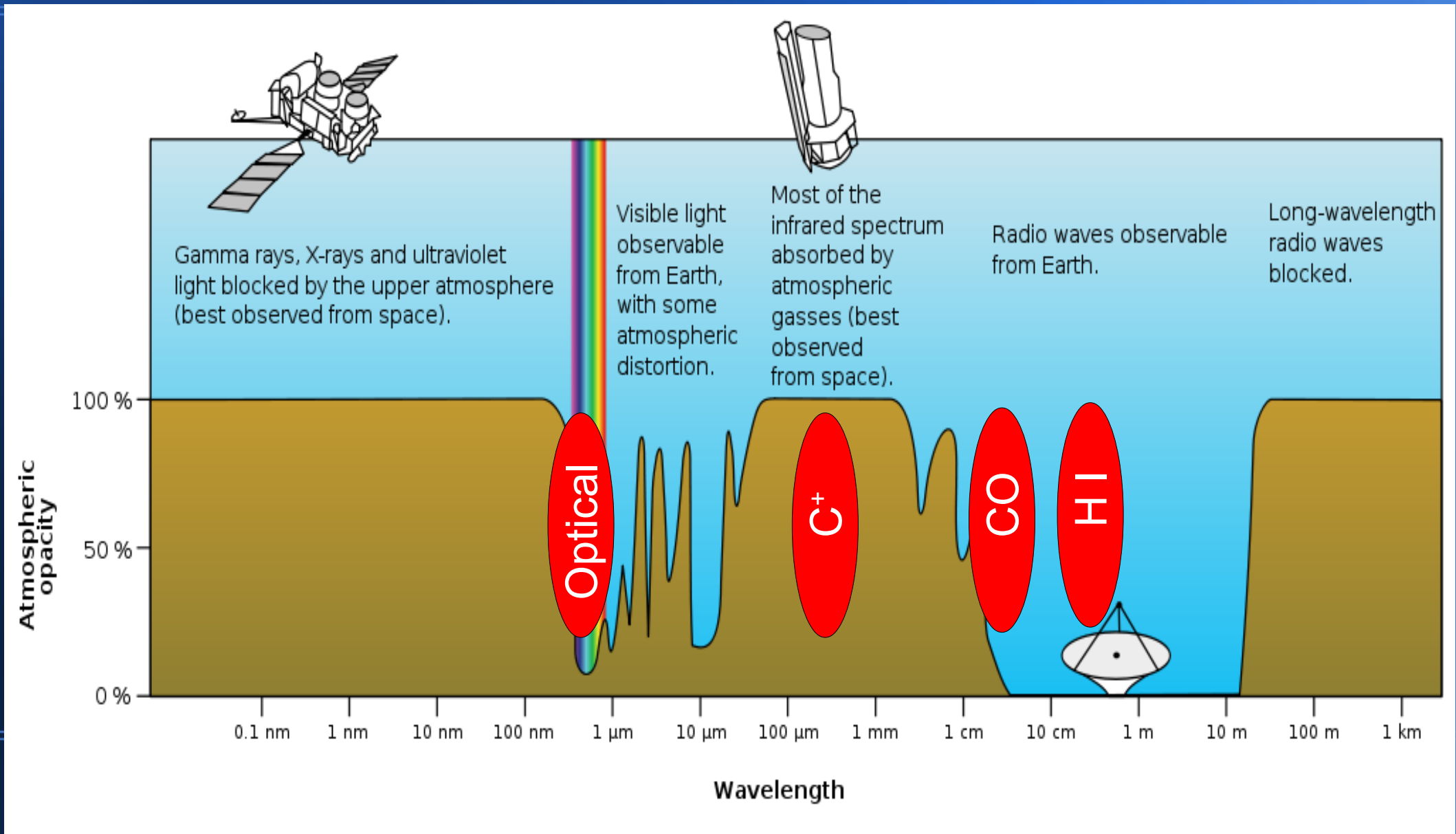
- Galactic Observations of Terahertz C^+

  → 1.9 Thz (158μm)

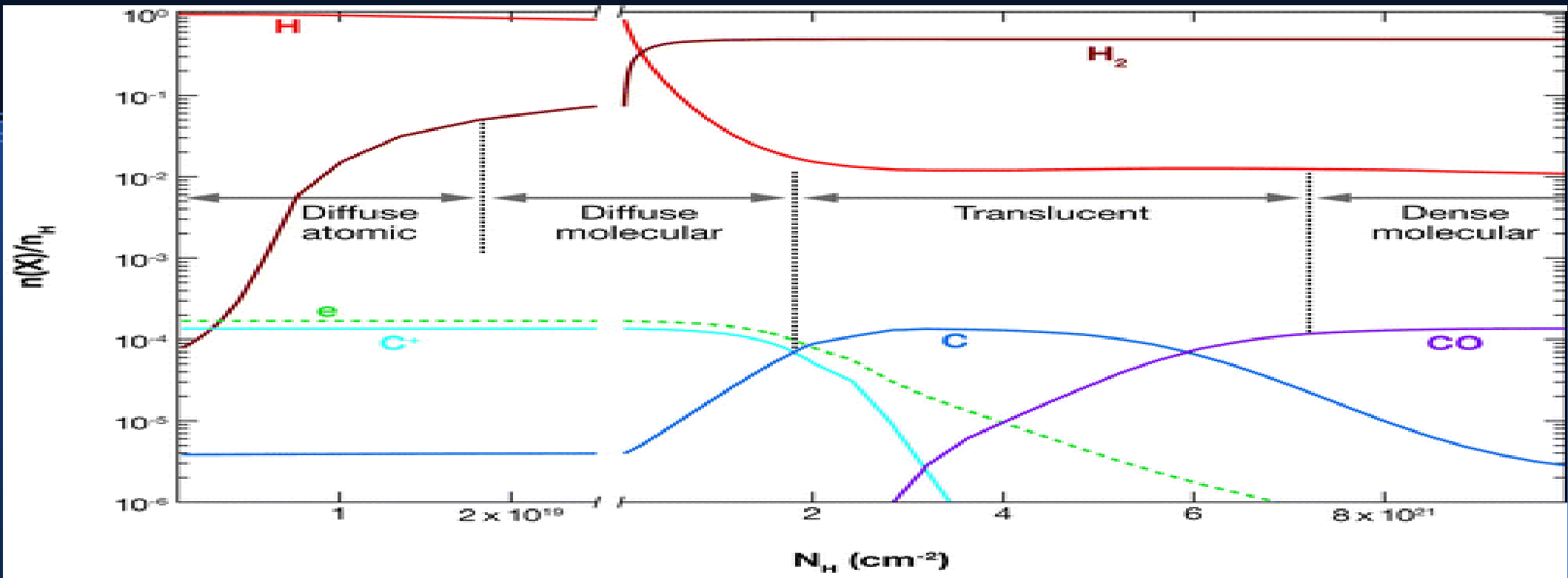
- C II is a density and temperature sensitive probe of diffuse clouds and PDRs
- Herschel is able to reveal individual cloud components

  → Full program will observe ~900 LOS

Multi-wavelength Observations



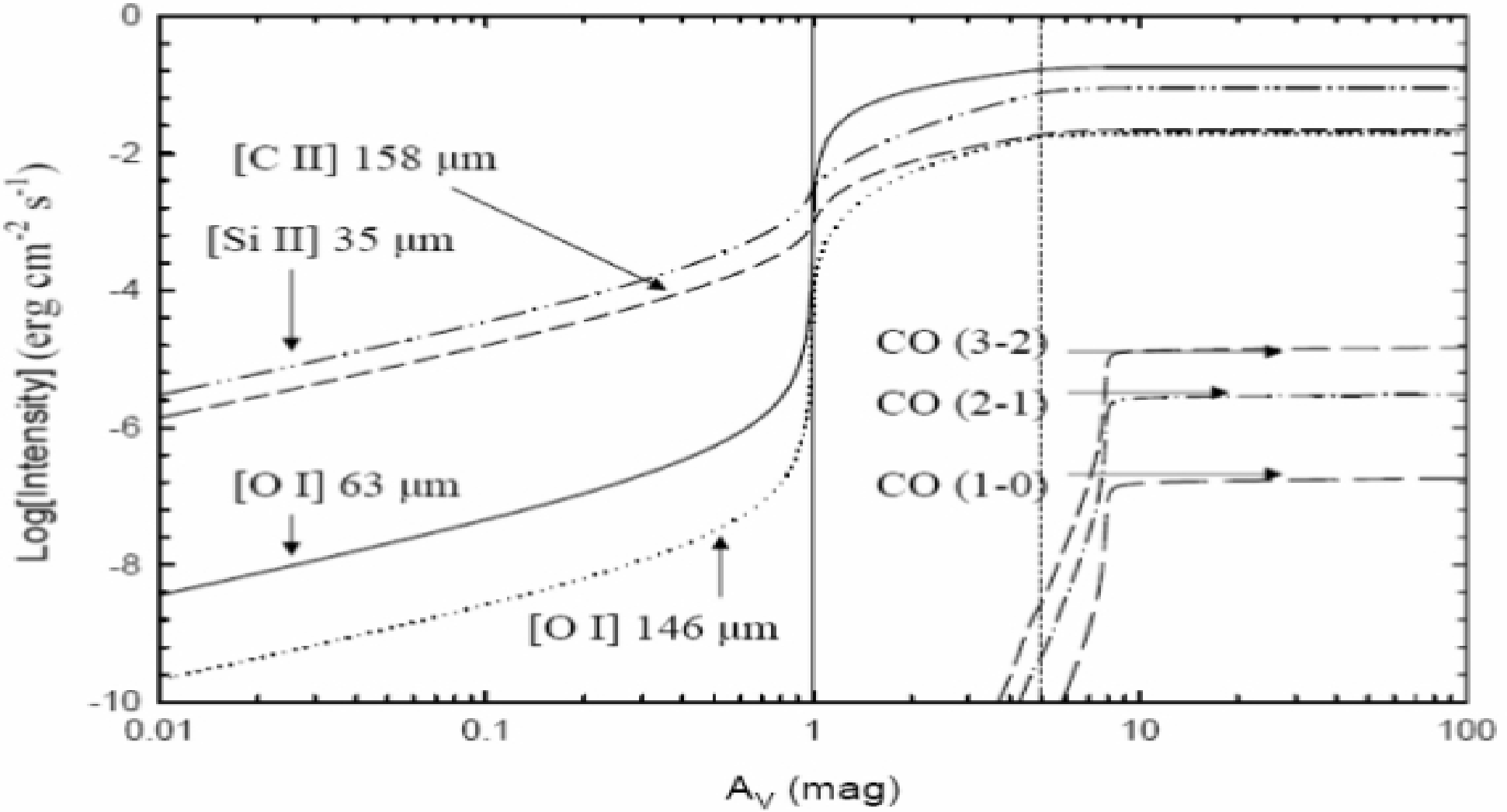
Cloud Type by Composition



Snow TP, McCall BJ. 2006.
Annu. Rev. Astron. Astrophys. 44:367–414

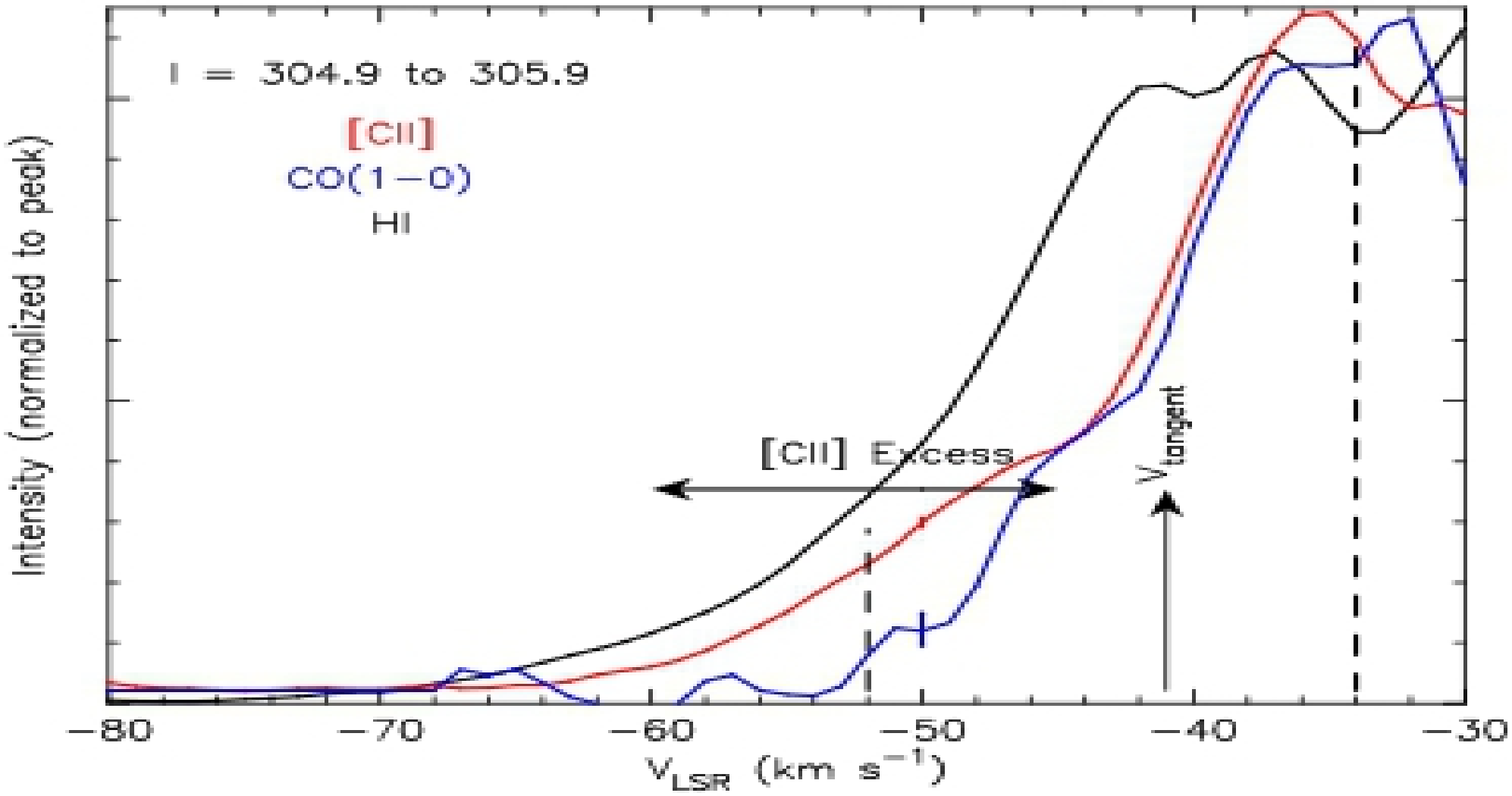
Property	Cloud type			
	Diffuse atomic	Diffuse molecular	Translucent	Dense molecular
Defining characteristic	$f^n_{H_2} < 0.1$	$f^n_{H_2} > 0.1$ $f^n_{C+} > 0.5$	$f^n_{CO} < 0.9$ $f^n_{C+} < 0.5$	$f^n_{CO} > 0.9$
A_V (minimum)	0–~0.2	~0.2–~1	~1–~5	~5–~10
Typical n_H (cm^{-3})	1–100	100–500	500–5000	10^4–10^6
Typical T (K)	30–150	30–100	15–50	10–50
Observational techniques	UV/visible absorption, H I radio emission	UV/visible/IR absorption, radio absorption	Visible/UV, IR absorption, radio absorption/emission	IR absorption, radio emission

CO Dark Gas



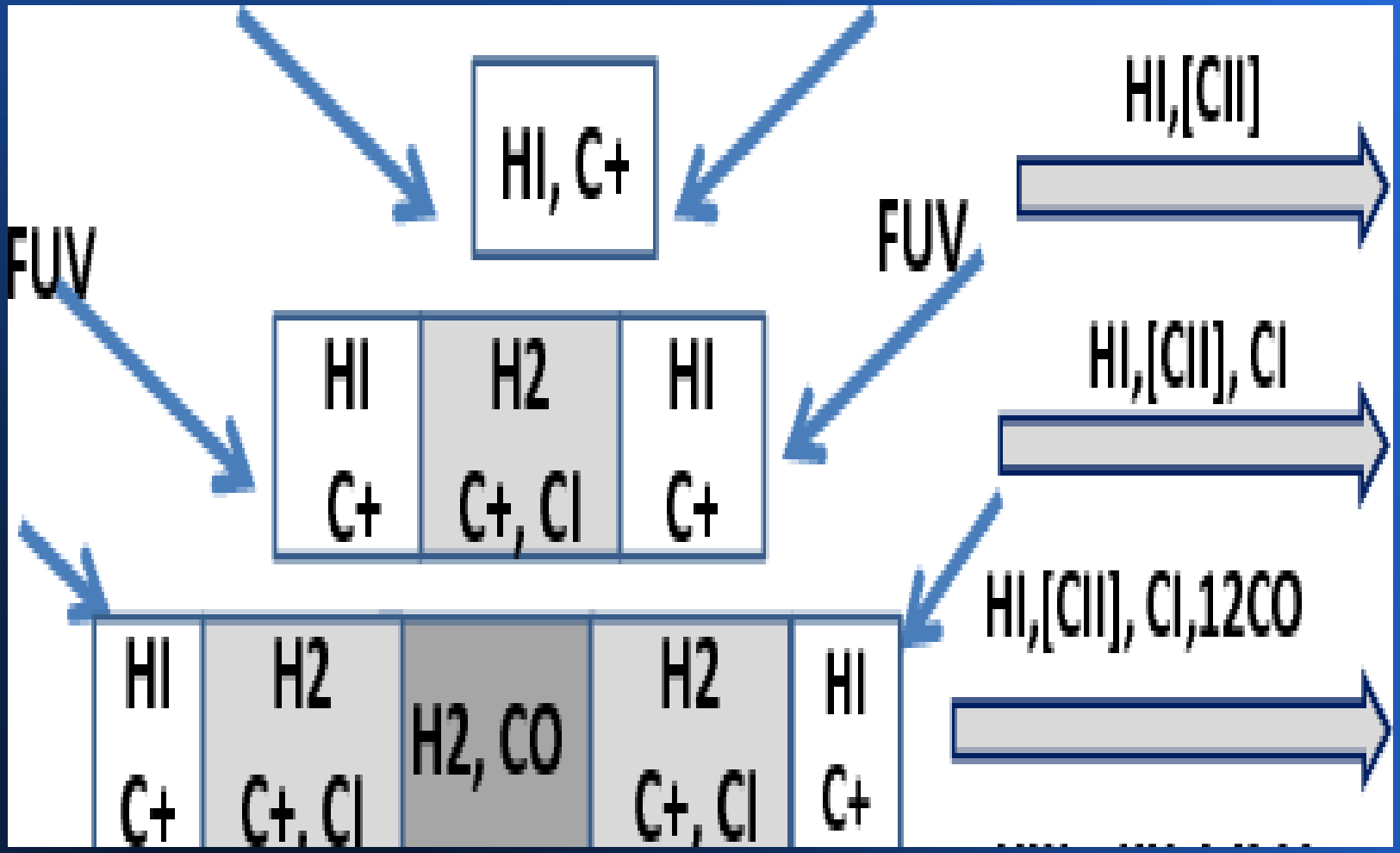
(Abel et al. 2005)

GOTC+: CO Dark Gas in Spiral Arms



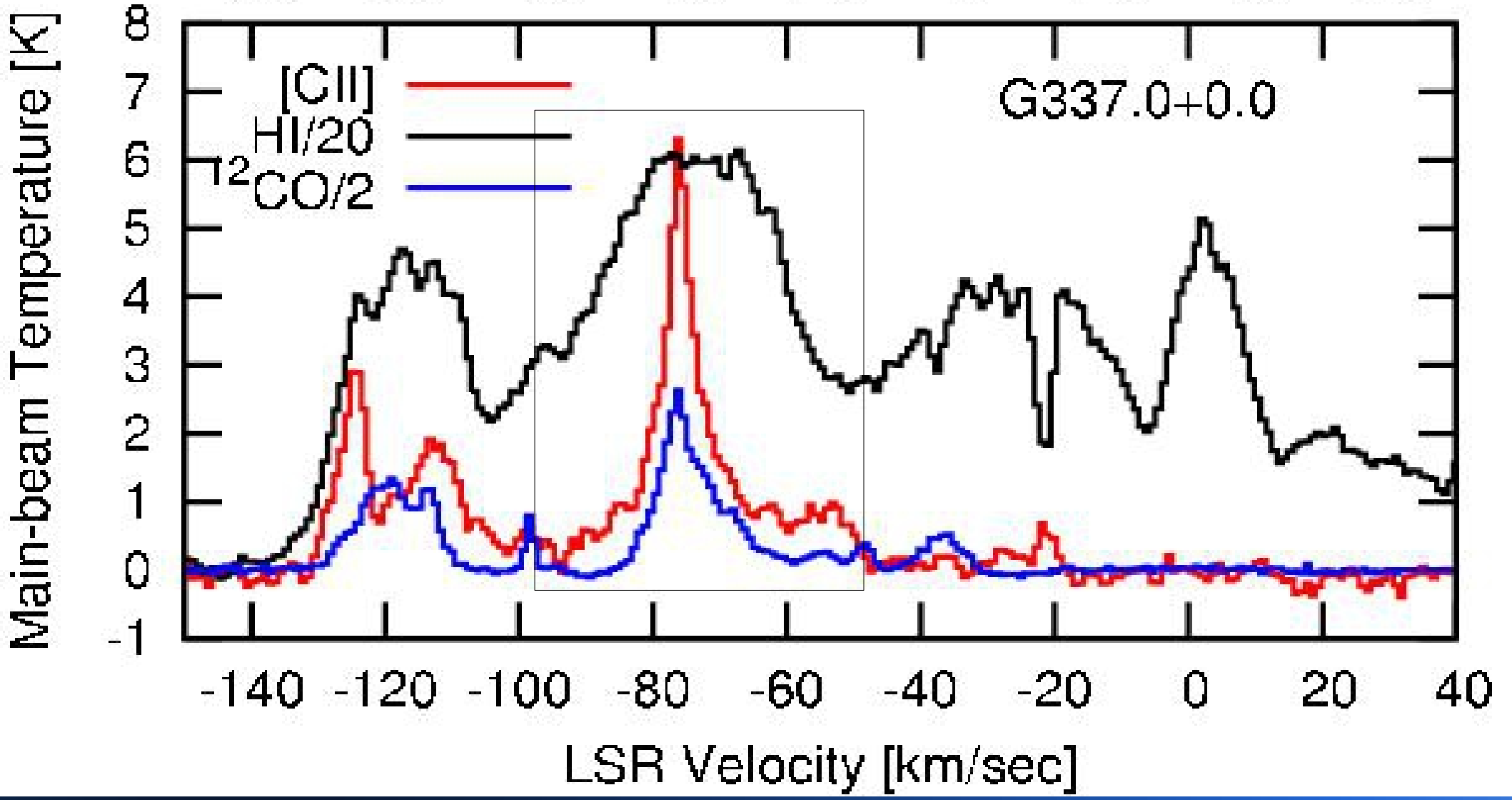
(Velusamy et al. 2015)

GOTC+: Emission Indicators

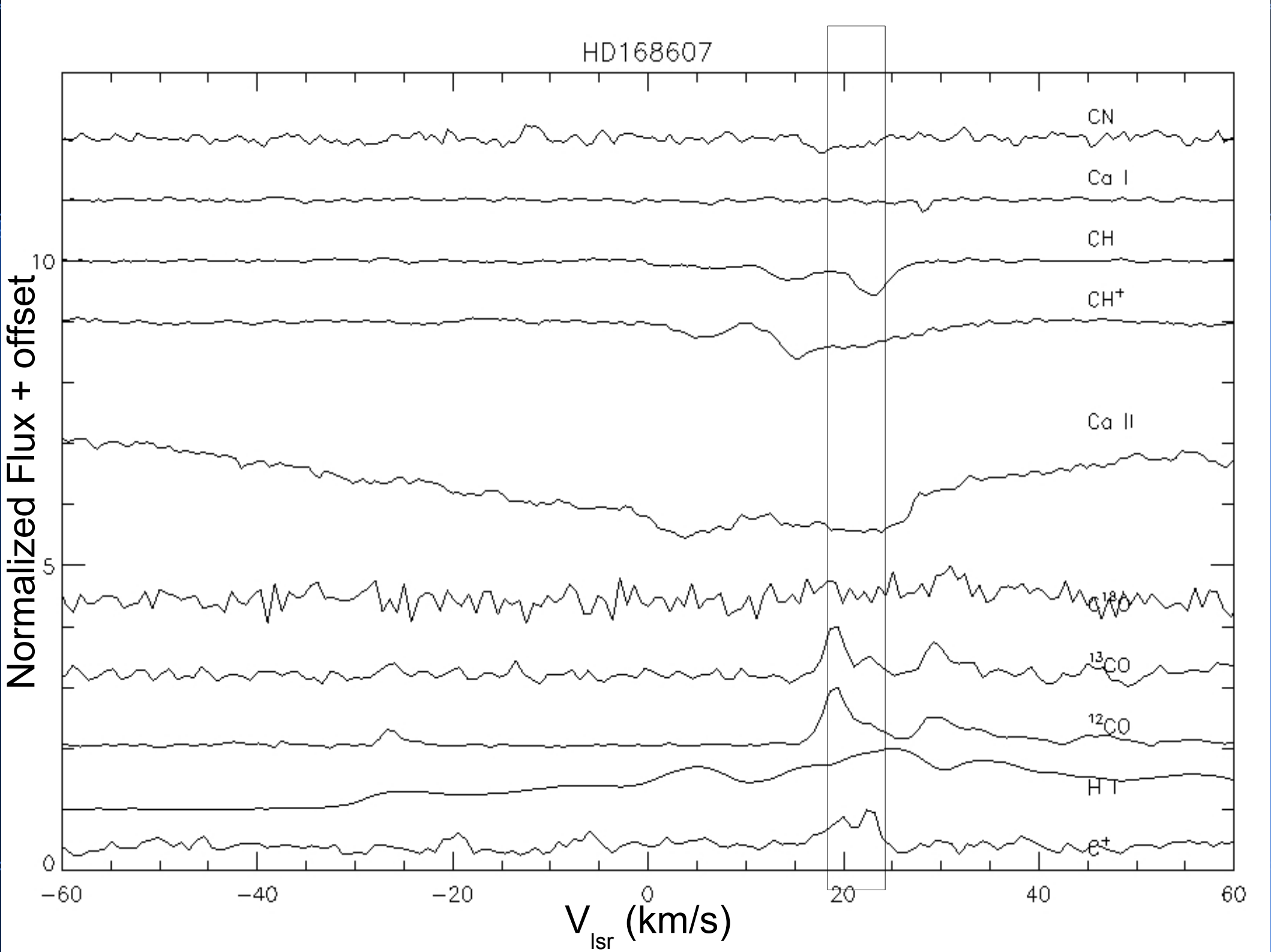


(Velusamy et al. 2010)

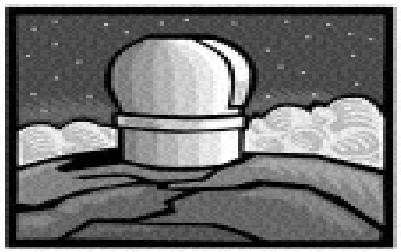
GOTC+: Velocity Distribution of Tracers in Emission



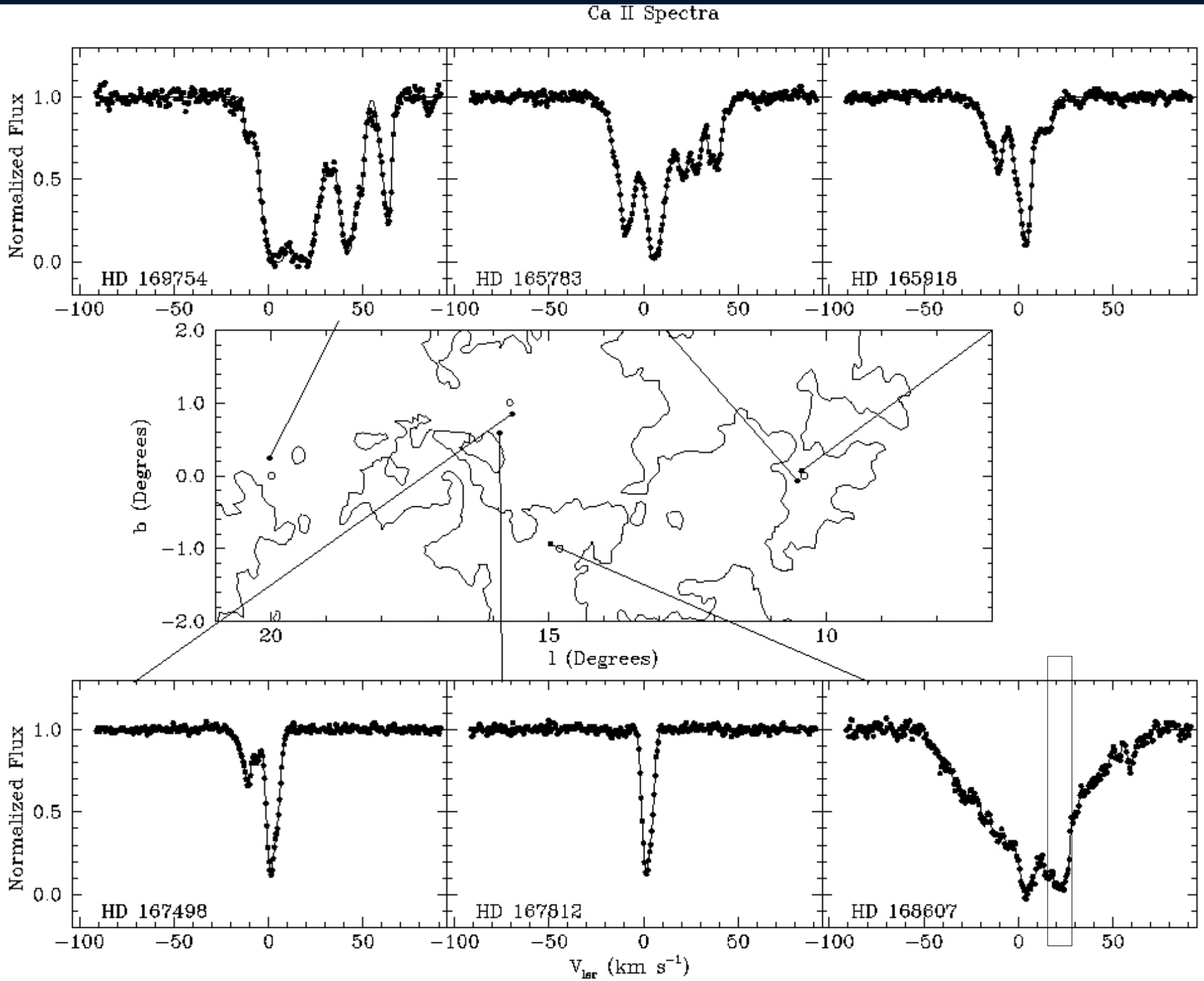
(Pineda et al. 2013)

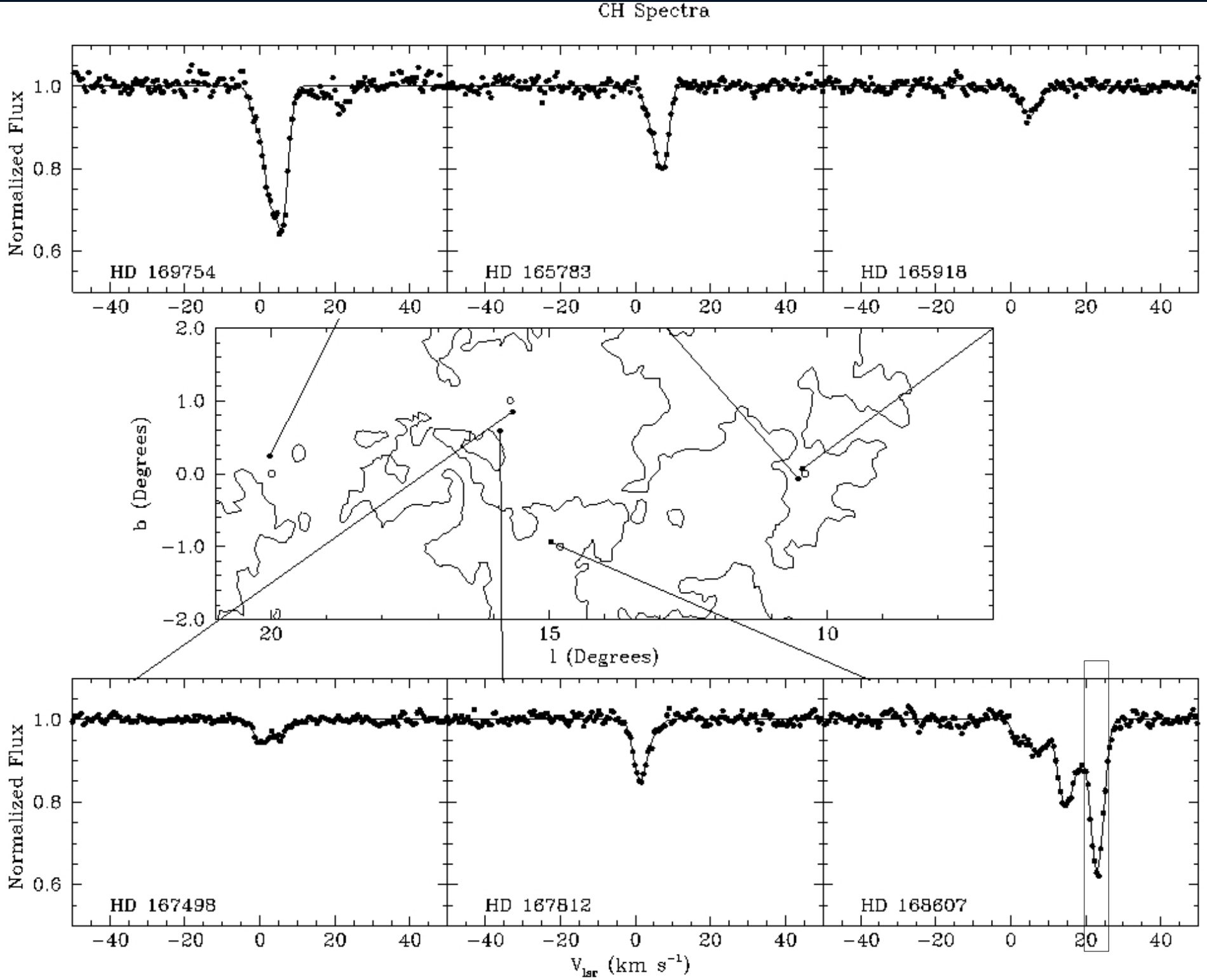

HD168607
CN
Ca I
CH
CH+
Ca II
C18O
13CO
12CO
H I
C+
Normalized Flux + offset
10
5
0
−60
−40
−20
0
20
40
60
Vlsr (km/s)

Species in Absorption



(Pan et al. 2005)

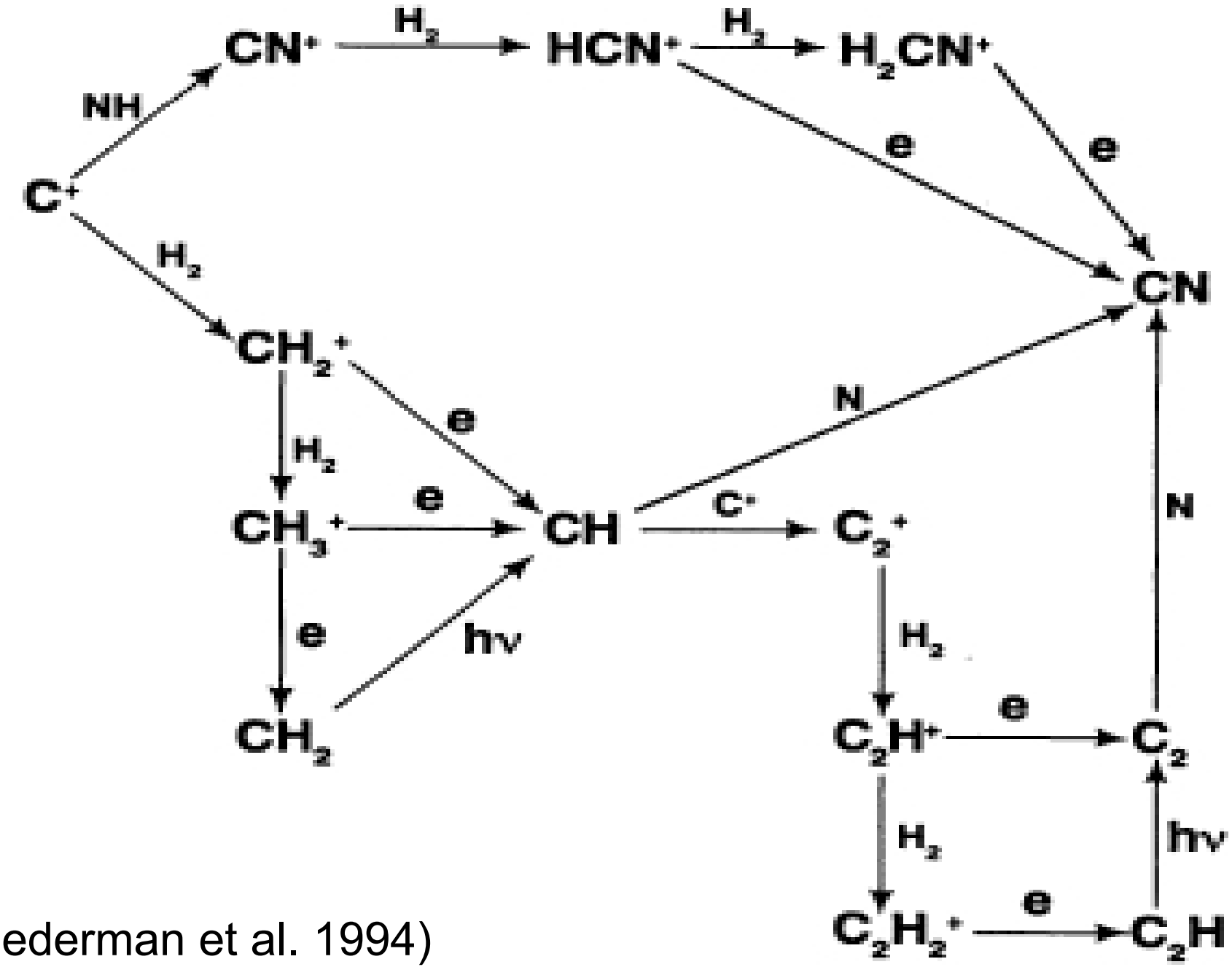

Ca II Spectra
Normalized Flux
HD 169754
HD 165783
HD 165918
b (Degrees)
l (Degrees)
HD 167498
HD 167812
HD 168607
V_{lsr} (km s^{-1})


CH Spectra
Normalized Flux
1.0
0.8
0.6
HD 169754
HD 165783
HD 165918
−40
−20
0
20
40
2.0
1.0
0.0
−1.0
−2.0
b (Degrees)
20
15
10
l (Degrees)
HD 167498
HD 167812
HD 168607
V_{lsr} (km s^{-1})

Statistics

	Components	Ca II Only	Ca II + K I CH + CH^+	with CN
C^+ only	5	1		
H I only	36	9	8	1
^{12}CO only	5	1		1
$^{12}CO/^{13}CO$ only	5	1	2	1
C^+ + H I	5	2		
C^+ + ^{12}CO				
C^+ + $^{12}CO/^{13}CO$	2	1		1
H I + ^{12}CO	7	2		
H I + $^{12}CO/^{13}CO$	3	1	1	
C^+ + H I + ^{12}CO	2			
All	8	4		

Chemistry



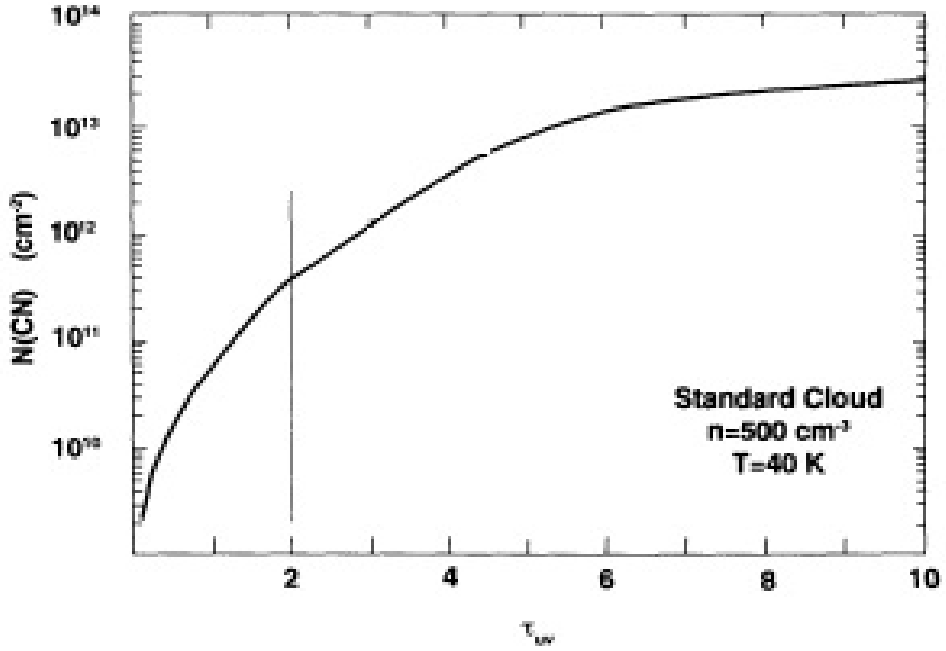
(Federman et al. 1994)

Density from Absorption Measurements

Sightline	V_{lsr}	T_{01}	I_{UV}	τ_{UV}	n	N_{CH}	N_{C_2}	N_{C_2}(p)	N_{CN}	N_{CN}(p)
HD 168607	18.3	35	1	9.86	1600	4.80×10^{12}	...	2.68×10^{12}	2.60×10^{12}	2.48×10^{12}
HD 169754	5.5	35	1	7.81	1600	2.80×10^{13}	...	2.09×10^{13}	3.40×10^{13}	2.05×10^{13}
HD 169754	-1.0	35	1	7.81	1600	6.40×10^{12}	...	4.77×10^{12}	6.60×10^{12}	4.69×10^{12}
HD 240179	0.3	65	1	2.42	≤ 275	6.60×10^{12}	...	3.89×10^{12}	$\leq 8.40\times10^{11}$	8.33×10^{11}
HD 240179	-1.5	65	1	2.42	≤ 450	4.00×10^{12}	...	3.57×10^{12}	$\leq 8.40\times10^{11}$	8.56×10^{11}
HD 240179	-6.6	65	1	2.42	≤ 550	3.10×10^{12}	...	3.24×10^{12}	$\leq 8.40\times10^{11}$	8.22×10^{11}
HD 240183	-1.3	65	1	1.8	≤ 200	6.10×10^{12}	...	3.32×10^{12}	$\leq 5.50\times10^{11}$	5.77×10^{11}

$$N(C_2) = \frac{k_1 x(C^+) N(CH) n \alpha}{G(C_2) + k_2 x(O) n + k_3 x(N) n}$$

$$N(CN) = \frac{[k_3 x(N) N(C_2) + k_4 x(N) N(CH) + k_5 x(C^+) N(NH) \alpha] n}{G(CN) + k_6 \bullet x(O) n}$$

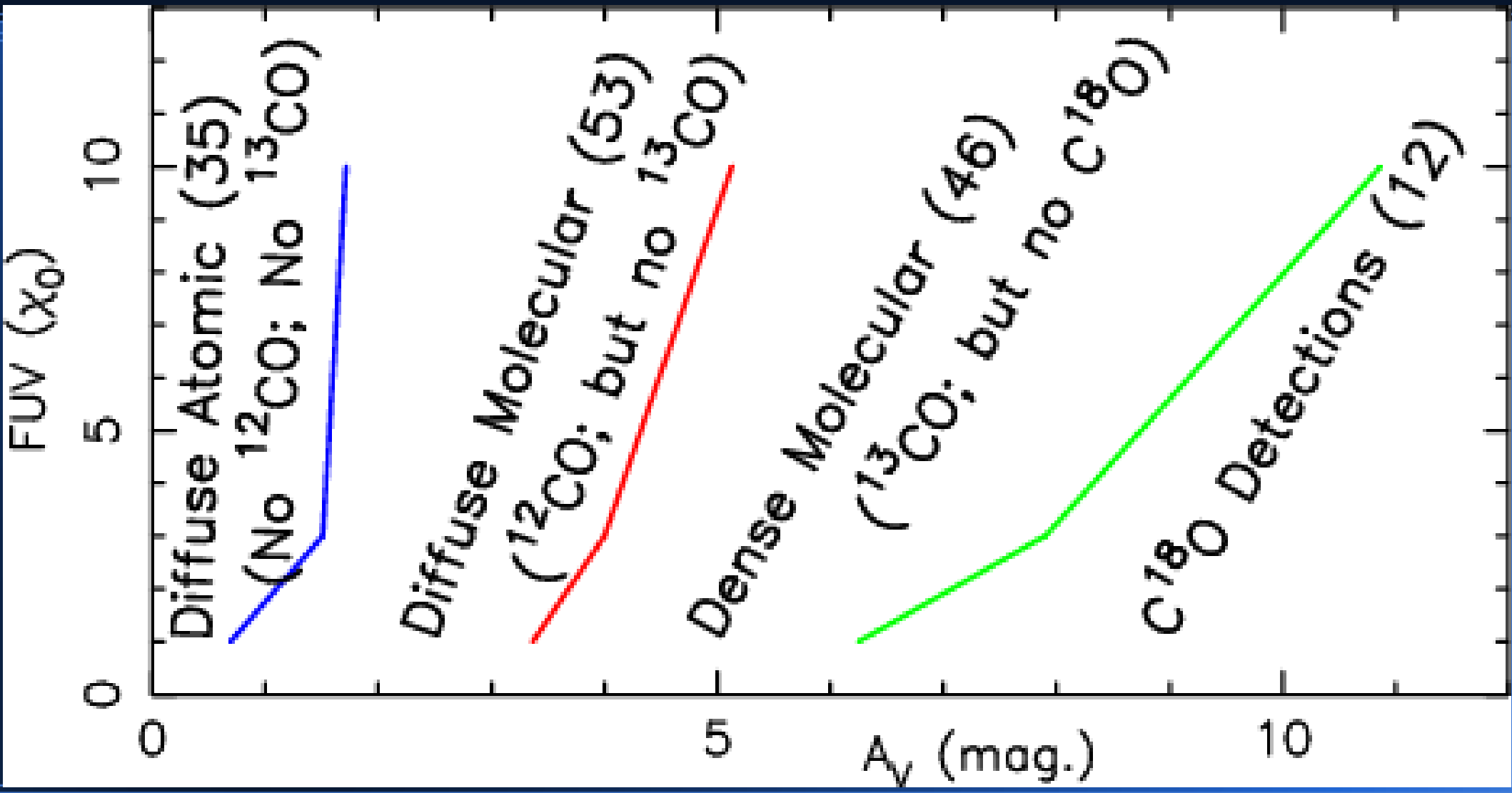


(Federman et al. 1994)

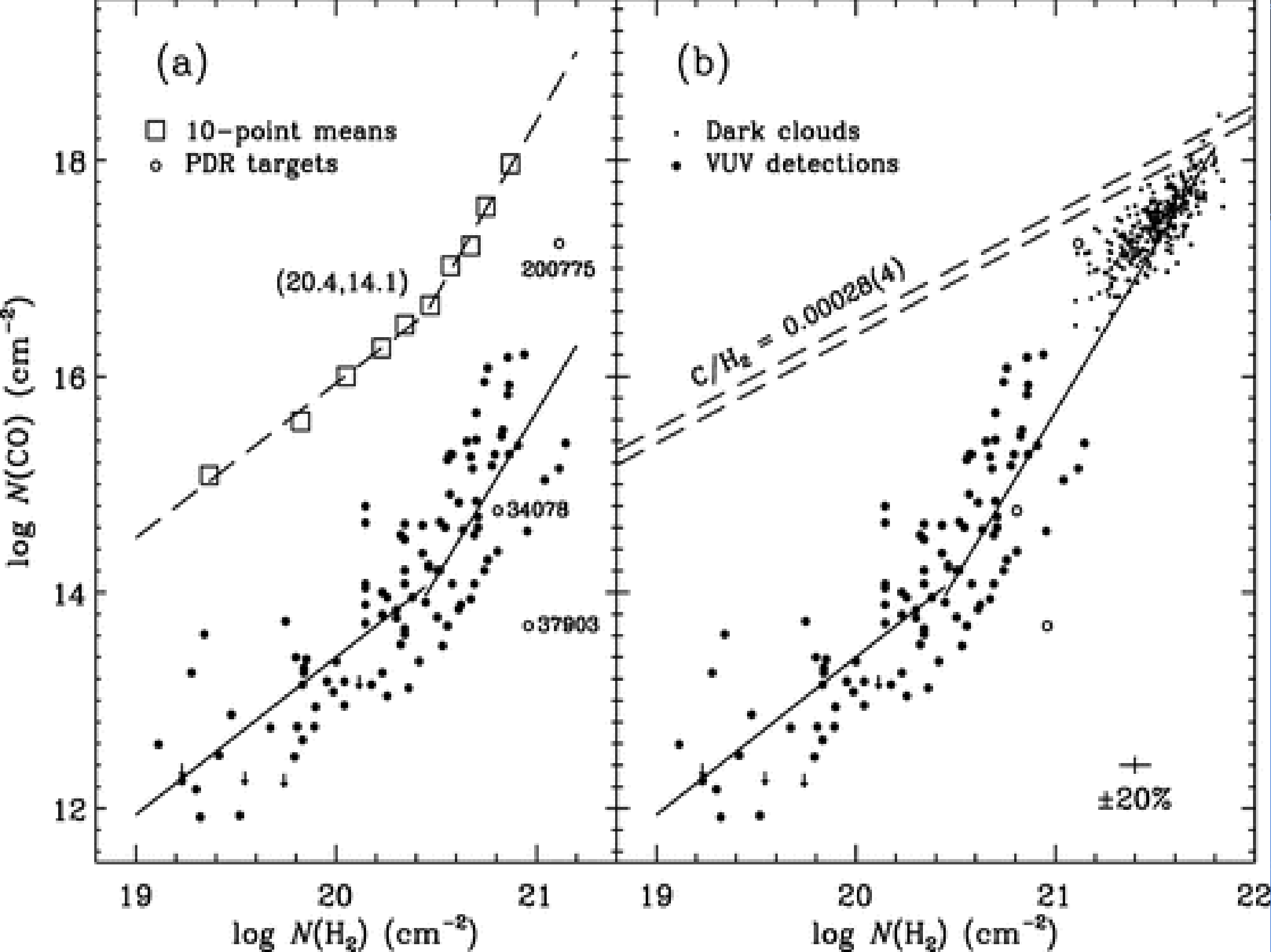
Summary

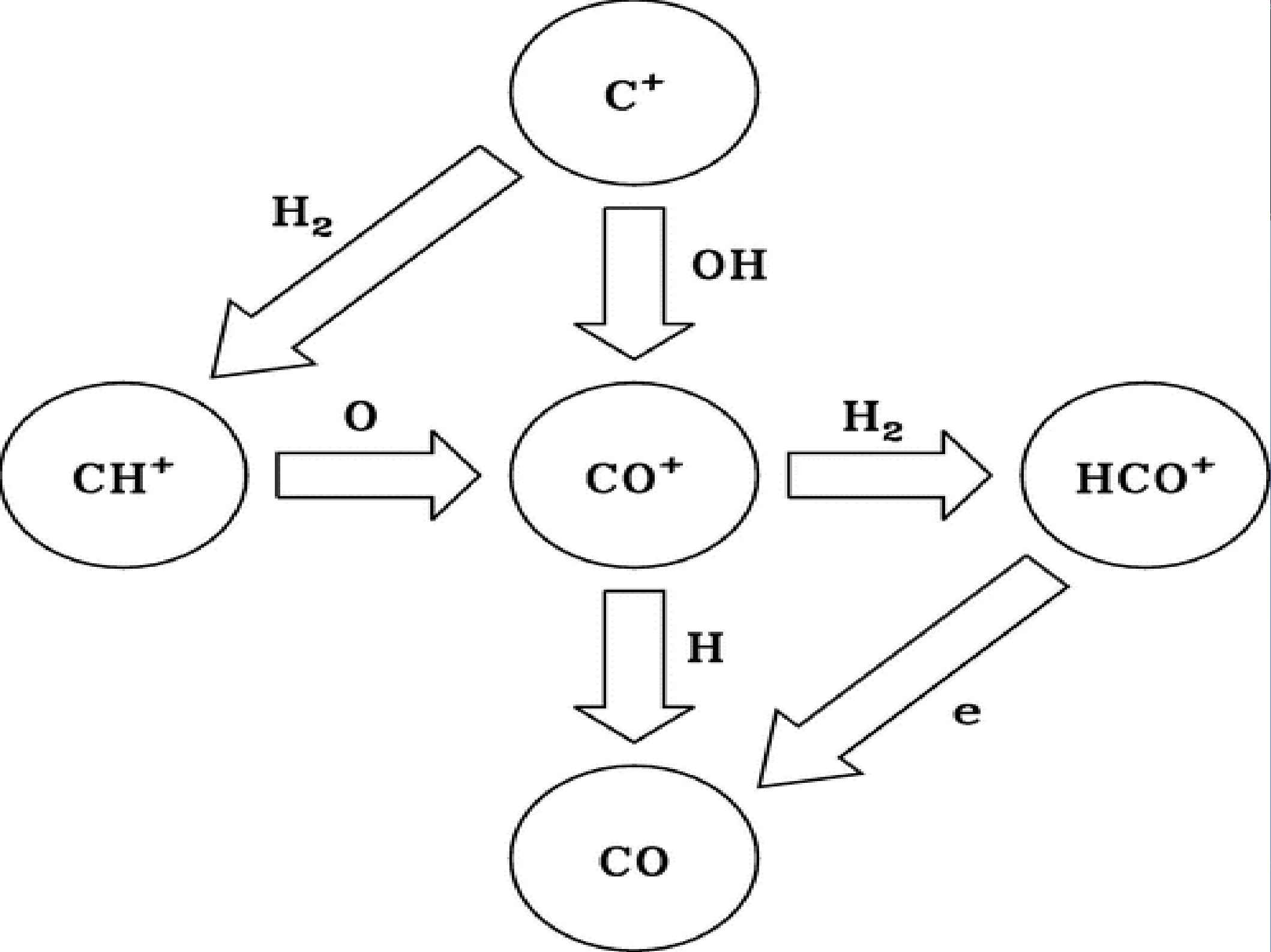
- GOTC+ / Optical Statistics
  - CN associated with CO / Diffuse Molecular Gas
- CH/CN Chemistry
  - → Density
- Future Observations
  - OH Emission
  - CO/^{13}CO/C_2 absorption

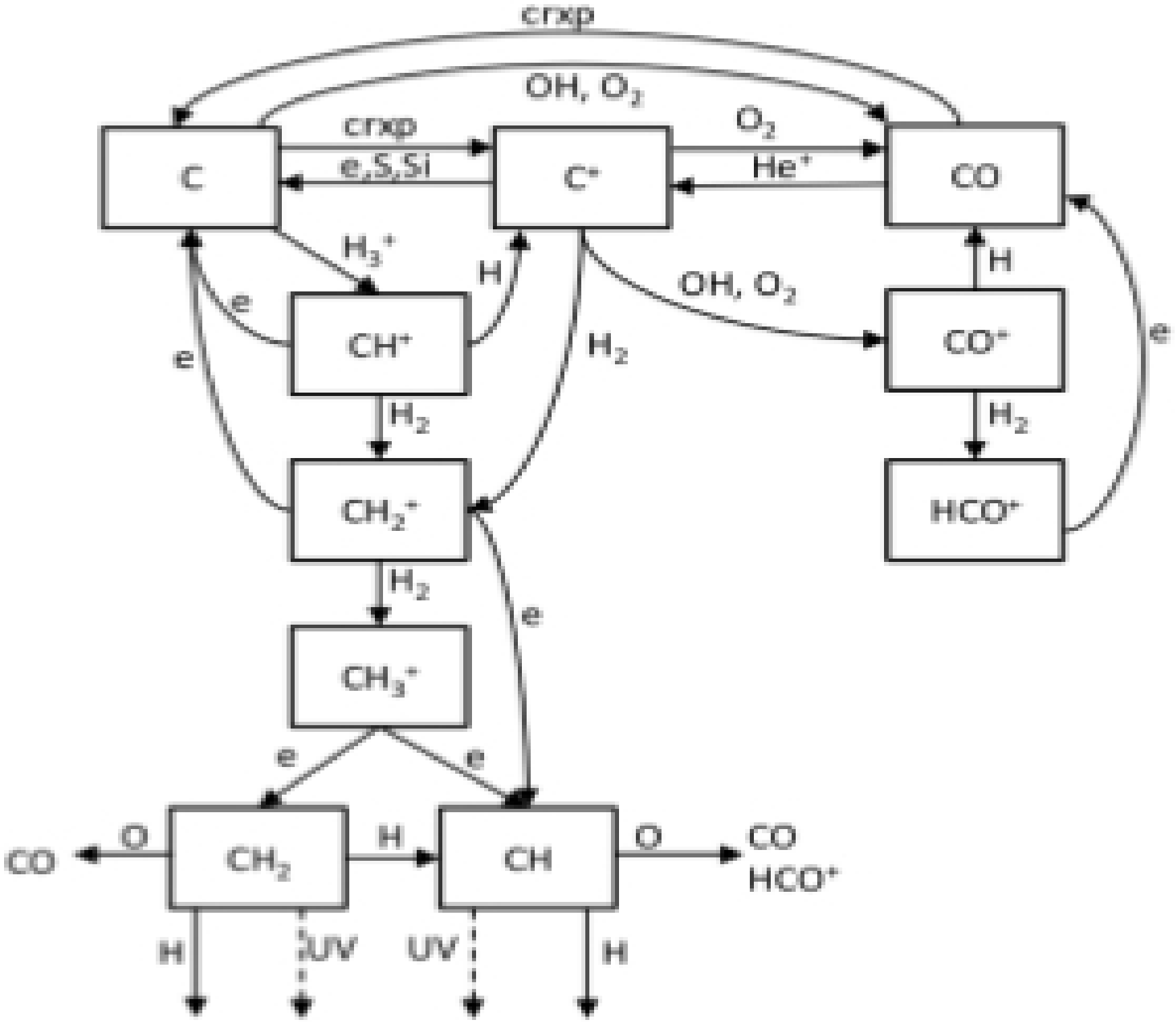
GOTC+: Cloud Type by A_V and FUV



(Velusamy et al. 2010)


(a)
10-point means
PDR targets
(20.4,14.1)
200775
34078
37903
(b)
Dark clouds
VUV detections
c/H₂ = 0.00028(4)
±20%
log N(CO) (cm⁻²)
log N(H₂) (cm⁻²)
12
14
16
18
19
20
21
22


C+
H2
OH
CH+
O
CO+
H2
HCO+
H
e
CO


crxp
OH, O2
crxp
O2
C
e,S,Si
C+
He+
CO
H3+
H
H
OH, O2
e
CH+
CO+
e
H2
H2
H2
CH2+
HCO+
H2
e
CH3+
e
e
CO
O
CH2
H
CH
O
CO
HCO+
H
UV
UV
H

RATES AND RATE CONSTANTS

Reaction	Rate/Rate Constant	Value ($s^{-1}/cm^3\ s^{-1}$)	Notes
$C^+ + CH \rightarrow C_2^+ + H$	k_1	3.0×10^{-10}	1
		5.1×10^{-10}	2, 3
$C_2 + O \rightarrow CO + C$	k_2	4.0×10^{-11}	4, 5
$C_2 + N \rightarrow CN + C$	k_3	1.7×10^{-11}	2, 5
$CH + N \rightarrow CN + H$	k_4	2.0×10^{-11}	5, 6
$C^+ + NH \rightarrow$ all products	k_5	2.8×10^{-10}	2
		5.6×10^{-10}	2, 3
$CN + O \rightarrow CO + N$	k_6	1.8×10^{-11}	5, 7
$C_2 + h\nu \rightarrow 2C$	$G(C_2)$	2.0×10^{-10}	8
$CN + h\nu \rightarrow C + N$	G(CN)	1.0×10^{-10}	9

NOTES.—(1) Federman & Huntress 1989; (2) Derived in this work; (3) Should lower densities apply; (4) Estimate; (5) Rate constant has a temperature dependence of $(T/300)^{0.5}$; (6) Messing et al. 1981; (7) Schmatjko & Wolfrum 1976; (8) Pouilly et al. 1983, corrected for appropriate radiation field; van Dishoeck 1987; (9) Lavendy et al. 1987.

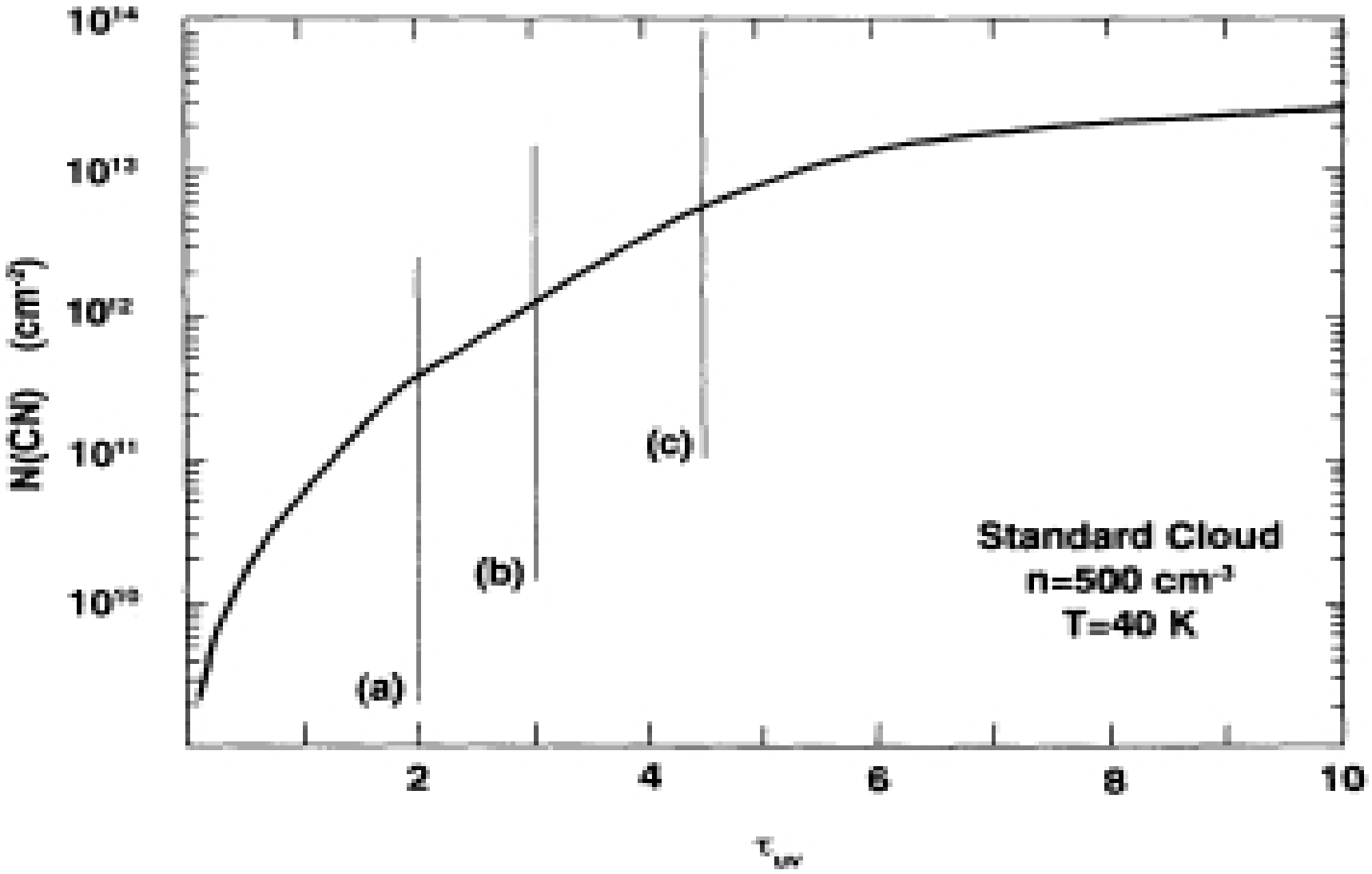
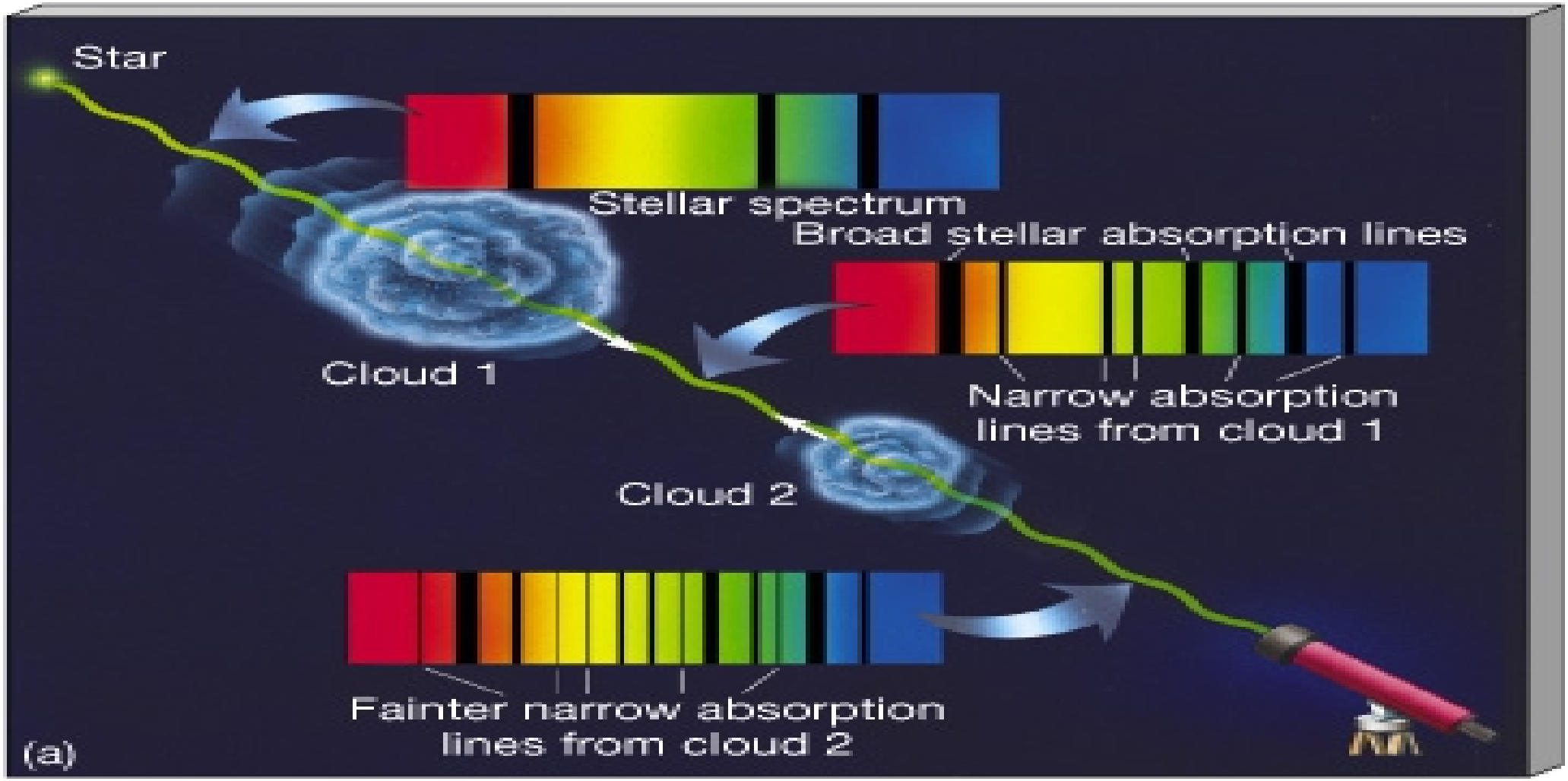
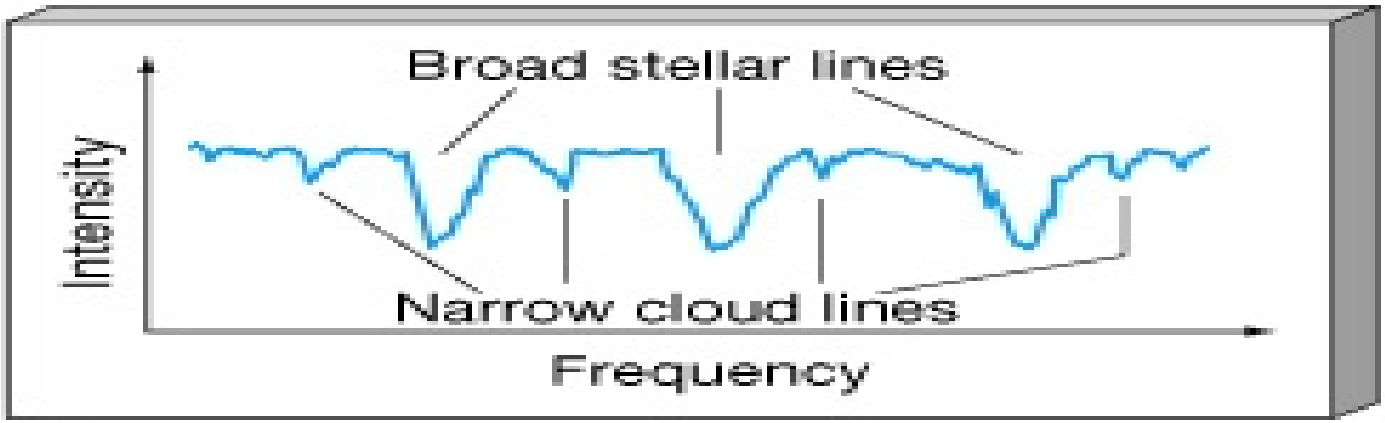


FIG. 5.—A plot of N(CN) vs. τ_{uv} indicating the positions of chemical transitions. (*a*) Where the conversion of C^+ into CO takes place. (*b*) Where production via the ion-molecule reaction $C^+ + NH$ equals production through neutral-neutral reactions involving C_2 and CH with N, with the neutral-neutral reactions dominating at larger τ_{uv}. (*c*) Where photochemical destruction is balanced by gas phase chemical destruction.


Star
Stellar spectrum
Broad stellar absorption lines
Cloud 1
Narrow absorption lines from cloud 1
Cloud 2
Fainter narrow absorption lines from cloud 2
(a)


Broad stellar lines
Intensity
Narrow cloud lines
Frequency
(b)